



Particle Physics Division

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Title: Corrosion Tests on Aluminum Samples

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Abstract/Summary:

The CDF ISL cooling system which is basically made of aluminum and glycol water is used as the coolant was once found leaking. Pitting corrosion was possibly the cause and a series of tests was conducted to verify this speculation. Indeed pitting was observed after the aluminum samples were immersed in a solution with pH in the range of 4 to 9. Immersion of epoxy joint samples was done also in order to verify if the aqueous solution would make the adhesive joints detached.

(I) Introduction:

ISL, one of the CDF silicon detector systems, has been detected its cooling system leaking many years ago. The major leaks appeared occurred in those aluminum lines but not in the stainless steel ones. The chosen coolant was 90/10 mix of water/ethylene glycol with operating temperature about +6C. Since no inhibitor was used and acidity of this coolant was verified, pitting corrosion on this aluminum line which eventually led to the formation of a leak hole was possible to occur. This series of corrosion testing on a variety of aluminum samples was thus conducted to see if this might be happened. In addition, as there were concerns on the integrity of epoxy joints might be damaged after a long exposure to acidic coolant, aluminum glued samples immersed in acidic coolant was also conducted.

(II) Approach:

Two kinds of corrosion test were run. The first test was to verify the general corrosion and pitting corrosion of the aluminum samples. The second test was a functionality check on the epoxy glued joint on the aluminum base parts. Several kinds of aluminum alloy samples were made and they were immersed in different kinds of acidic solution. Since formic acid was found in the coolant sample, two types of solutions was prepared in Lab 6. The first kind was fresh-made with formic acid and water, and the second kind was the actual coolants sampled from the ISL cooling line. pH acidity of the solutions were adjusted by adding formic acid or distilled water as needed. All aluminum samples were then immersed completely in the solution inside the glassy containers. Visual checking on these samples periodically was made. Samples were then removed from the solutions, and then they were rinsed with clean water, hot-air dried and weighed during the first 475 days. As of the functionality test on the epoxy joint samples, one more solution other than the fresh formic acid and ISL coolant was used. This was distilled water and it was served as a reference.

(III) Solutions Preparation:

Glycol water sampled on May 10 2007 from ISL cooling line was used for the coolant solution. In addition to fresh-made formic acid, six kinds of solution were prepared:

1. Coolant solution with pH ~4.5, after addition of deionizing water;
2. Coolant solution with pH ~2, after addition of formic acid;
2p. same as 2 but without turbid precipitation;
3. Fresh formic acid with pH ~4.5;
4. Fresh formic acid with pH ~2;
5. Distilled water.

(IV) Samples Preparation:

Based on the aluminum alloys that ISL used in the cooling line, the following eight samples were made:

- Aluminum 1100
- Aluminum 5052
- Aluminum 6061
- Aluminum welding filler wire 4043
- Aluminum welding filler wire 5356
- Aluminum welded part with filler 4043
- Aluminum welded part with filler 5356
- Aluminum 6061 after heated treated to filler welding temperature

In addition to these samples, a couple of similar parts that were used in the ISL cooling line were added after the corrosion test had been started for 3 months. These parts were a prism holder and a tubing sample made of aluminum 1100 H-14.

For the epoxy functionality test, two kinds of epoxy were used. They were all belonged to 3M products - 2216 and DP190. The following epoxy joint samples on aluminum base parts were made:

- Droplet on aluminum 1100 sheet
- Dog-bone through tiny hole of aluminum 1100 sheet
- Lapped joint with aluminum 1100 sheet, four epoxy sides exposed to solution

- Tubing joint with aluminum 6061, two epoxy sides exposed to solution
- Blind tubing joint aluminum 6061, one epoxy side exposed to solution

(V) Results on General Corrosion

Mass Loss checks were done on all the aluminum samples that were immersed in Solution 1, 2, 2p, and 3 at room temperature. As the sample sizes and shapes were quite different, mass loss per each surface sample area was used for the report. These results are plotted on Charts 1, 2 and 3 where Chart 2 consists of ISL coolant at pH about 2 with and without turbid participants (Solutions 2 and 2p). Also, in order to simulate the ISL cooling condition, many samples were placed inside a refrigerator with temperature about +6C after 75 testing days elapsed and its corresponding results were shown on the same Chart 2. Not sure what had happened on Solution 3, it lost its acidity after one week and became neutral. Attempt to restore its pH value by adding more formic acid was made but it returned to neutral again in a week. Mass losses on these samples in Solution 3 was thus not very much and its results is presented here for reference uses only.

Mass losses due to acid attack was generally quite even over the entire surface. For comparison purpose, same scales of the X- and Y-axis were used in Charts 1, 2 and 3. From these results, the following were observed:

- No apparent mass loss in the first 100 days when coolant was with pH ~ 4.5, then small mass loss appeared after.
- Mass loss was very severe when solution was very acidic at pH ~ 2.
- Mass loss rate was much slower when solution temperature was colder at +6C.
- Aluminum filler wire 5356 lost mass most.
- Referring to Table 1, it appeared mass loss occurred more in non-turbid solution than turbid solution. In particular, the ISL tubing sample 1100 H-14 placed in the non-turbid solution lost mass several times quickly than the regular sample 1100 which was placed in turbid solution. On another comparison, the loss difference between 6061 and heated 6061 was not apparent.

The similar prism holder used in the ISL cooling line was placed in the non-turbid ISL coolant with pH about 2 (Solution 2p). This part was found dissolved completely after 42 days.

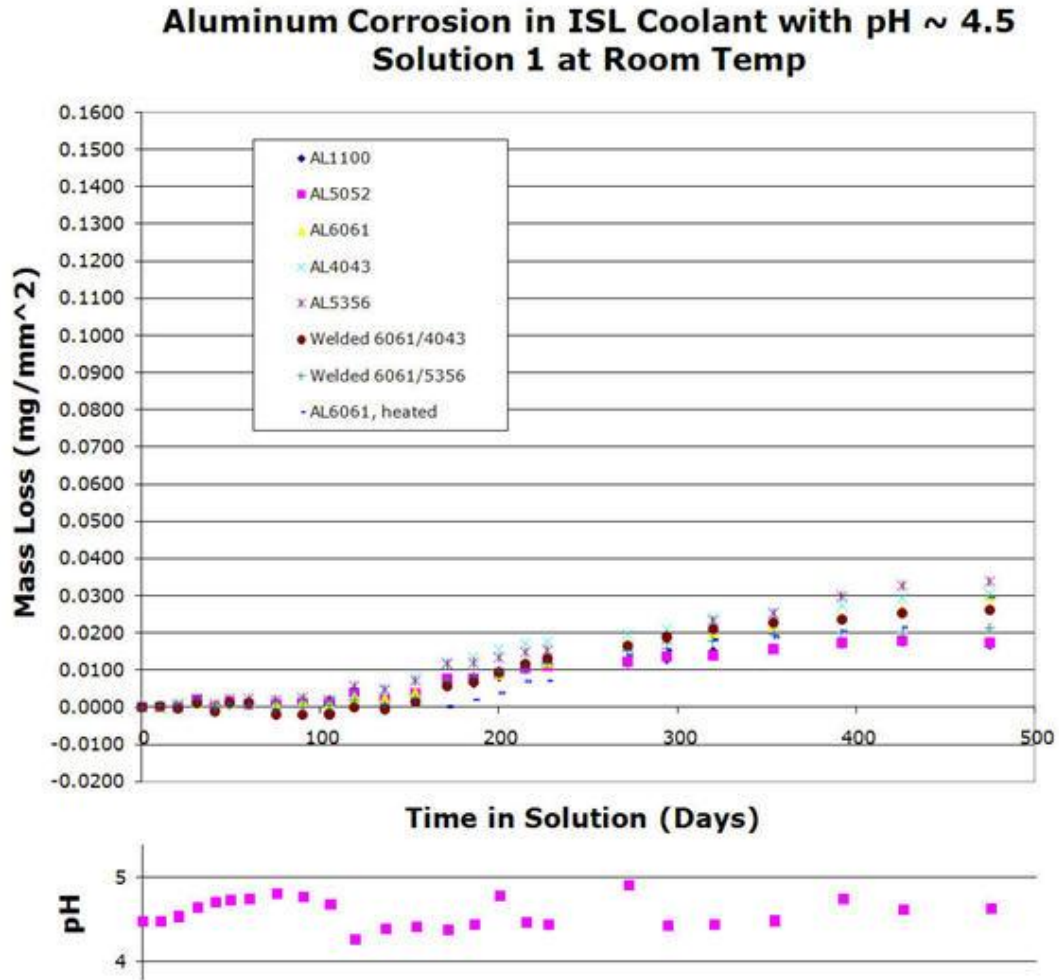


Chart 1. Mass Losses for Aluminum Samples in Solution 1

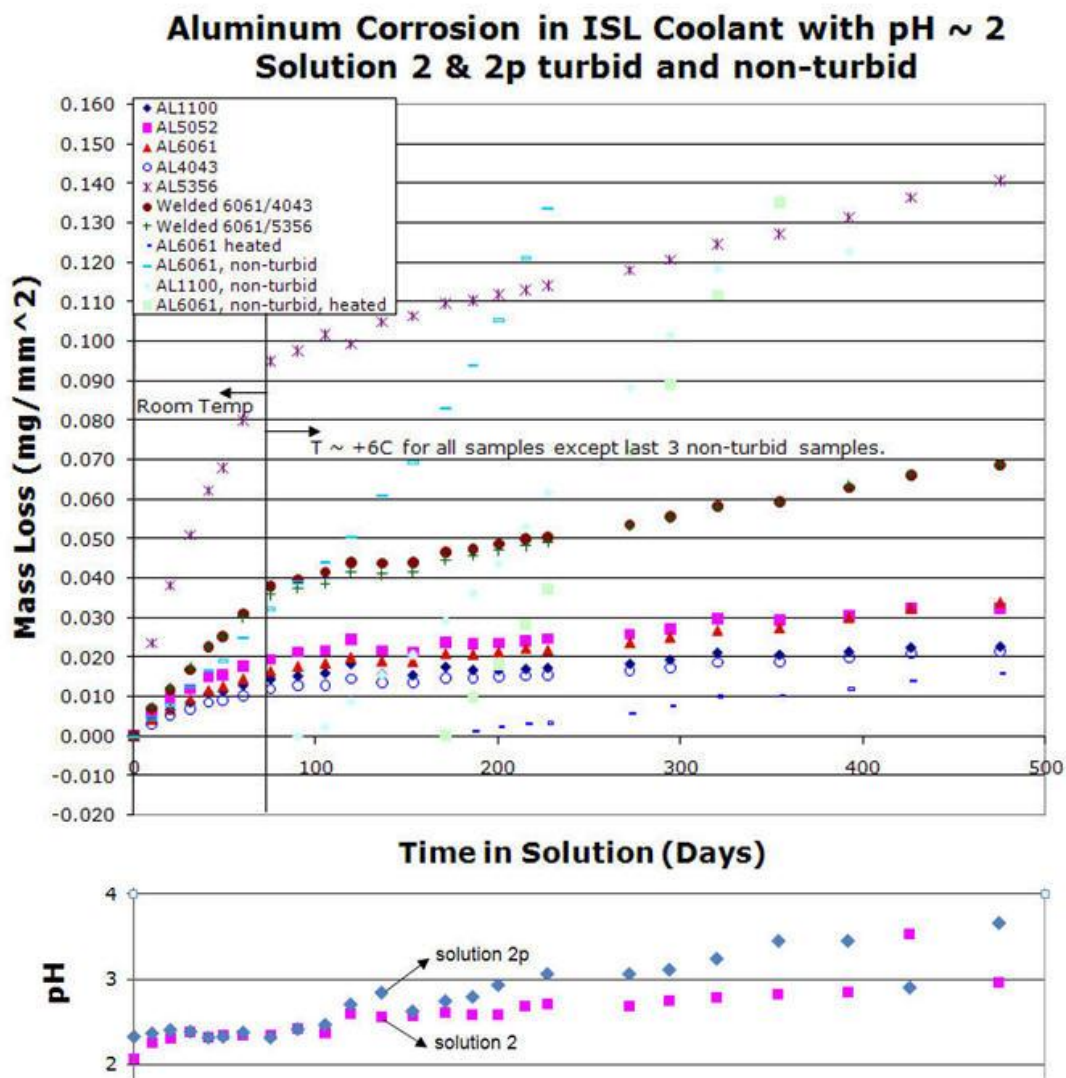


Chart 2. Mass Losses for Aluminum Samples in Solution 2 & 2p

Aluminum Corrosion in Formic Acid with pH ~ 4.5 Solution 3 at Room Temp

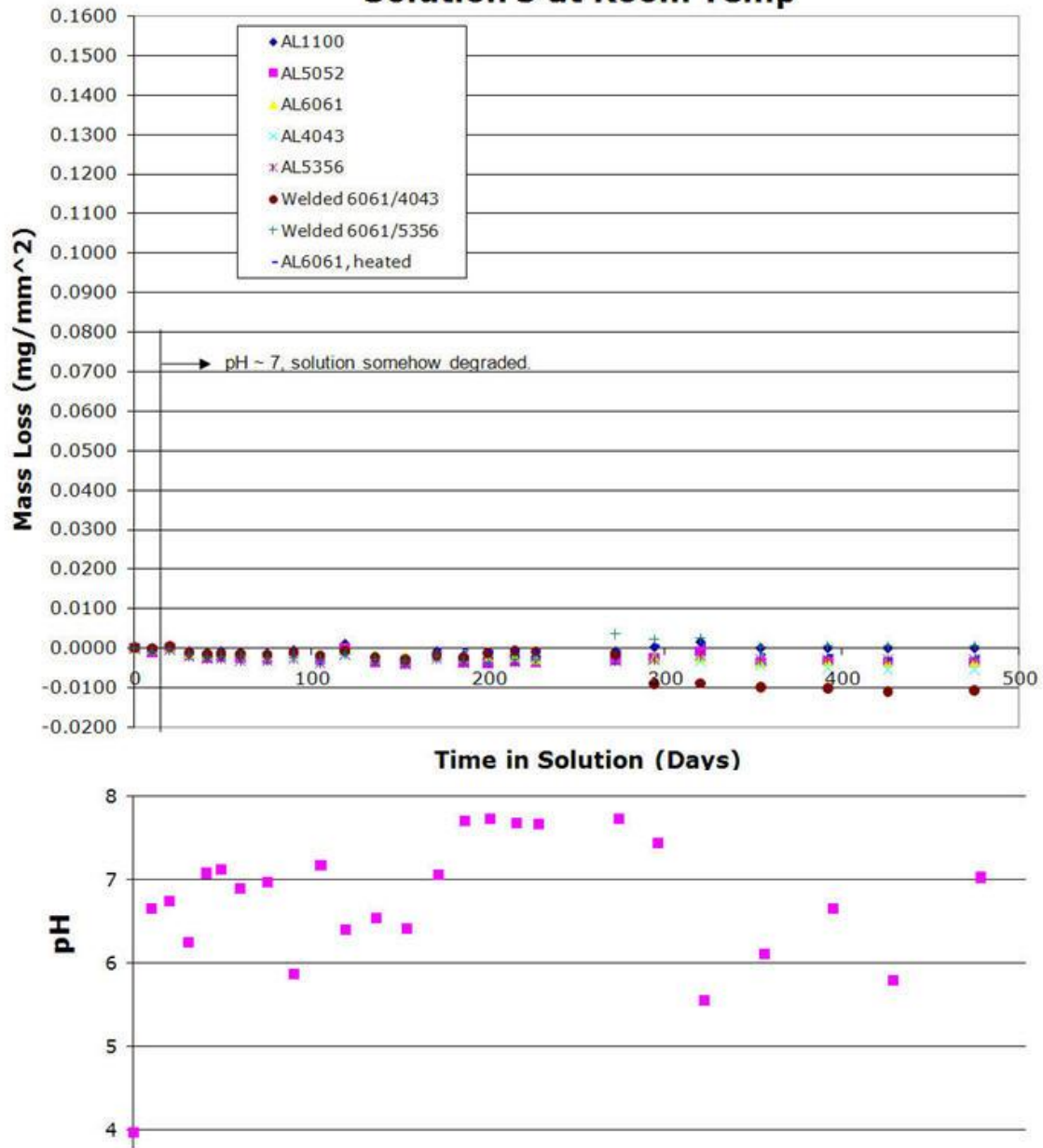


Chart 3. Mass Losses for Aluminum Samples in Solution 3

| | Turbid Solution | Non-turbid Solution | Turbid Solution | Non-turbid Solution |
|------------------|-----------------|---------------------|-----------------|---------------------|
| Days in solution | 100 | 100 | 300 | 300 |
| 1100 | .0161 | .0363 | .0194 | .1230 |
| 6061 | .0186 | .0443 | .0253 | .2016 |
| 6061w | .0060 | .0719 | .0161 | .2027 |

Table 1. Mass Losses Comparison between Turbid and Non-turbid Solutions

(VI) Results on Pitting corrosion

Pitting is the most common corrosion attack on aluminum alloy products. Pits form at localized discontinuities in the oxide film on aluminum. Since, in highly acidic or alkaline solutions, the oxide film is usually unstable and will suffer from general corrosion, pitting occurs only in a pH range of 4 to 9. It thus, pitting corrosion was expected to be happened in Solution 1 in which the pH was set about 4.5 but not in Solution 2. Signs of pitting with the gelatinous white corrosion products, which was supposed to be the alumina $\text{Al}(\text{OH})_3$ covering the pit, were first observed on aluminum welding filler wire 4043. It was so severe that it eventually broke the wire into 2 parts after 426 days. After 475 days, samples 1100, 6061 and welded assembly with 5356 were found with some slight pitting. However, pitting on these samples was stopped after the water rinsing step. Since the pitting corrosion appeared to be disturbed by the rinsing, it was thus decided no more rinsing and hence mass weighing were conducted because the major goal of the testing was to verify pitting corrosion but not general corrosion. After 1042 days, slight pitting was observed again on both samples 6061 (with and without heated). The final states of these samples were as shown in Figure 1.



Figure 1. Aluminum Samples in Solution 1 after 1042 days

Pitting corrosion was actually first found on aluminum samples in Solution 3 which was fresh-made formic acid with a pH set at 4.5. The acidity of this solution was changed to neutral gradually and it kept this neutrality although attempt was made in trying to put it back its acidity after two weeks. The unintentional neutrality of this solution thus provided the environmental condition for pitting corrosion to occur. First signs of pitting were observed after 136 days. Pitting on these aluminum samples was clearly envisioned after 171 days as shown in Figures 2, 3, 4 and 5 in which it showed pitting corrosion on 6061, 4043, 5356 and welded aluminum assembly with filler wire 4043. The white deposits on the welded assembly were removed and the aluminum was inspected further under microscope. The rim of the pit appears to be irregular as shown in Figure 6. With the focal dimensions obtained on the rim and on the bottom of pit, the depth of the pitting was estimated and it was about 360 microns. However, after this disturbance, all pitting corrosions including this one were found stopped even at the end of 1042 days.

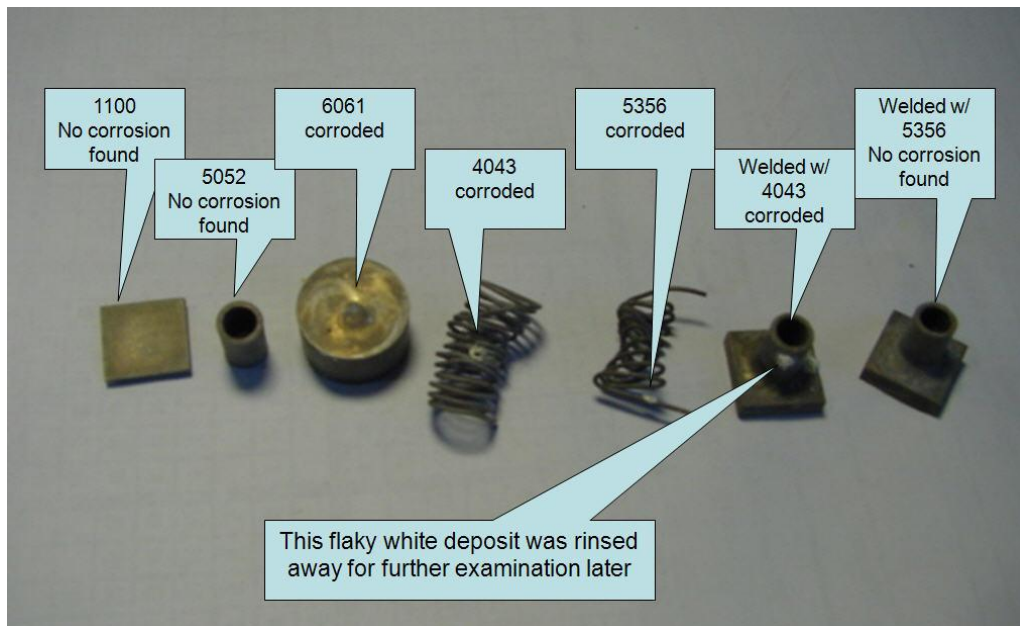


Figure 2. Aluminum Samples in Solution 3 after 171 Days



Figure 3. Aluminum Filler Wire 4043 in Solution 3 after 171 Days



Figure 4. Aluminum Filler Wire 4043 Solution 3 after 171 Days

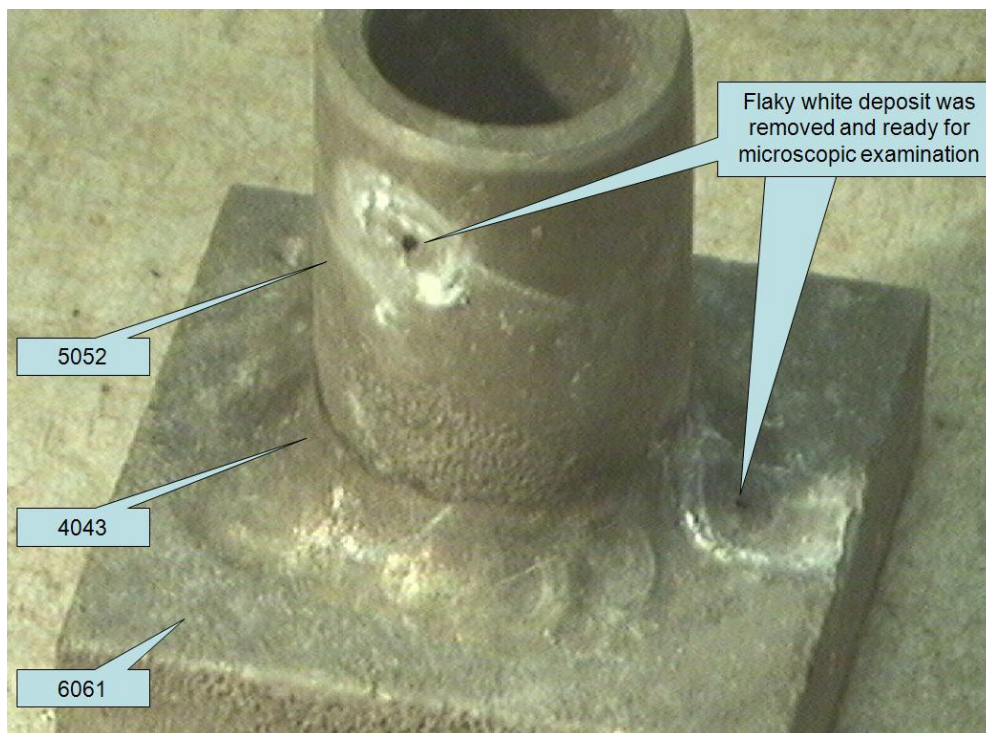


Figure 5. Aluminum Welded Assembly in Solution 3 after 171 Days



Figure 6. The Pit on Aluminum Welded Assembly in Solution 3

Pitting corrosion was also found for those epoxy-glued-aluminum 1100 samples in water (Solution 7 with pH ~7). It was started after 25 days and remained this state at the end of 1042 days as shown in Figures 7 and 8.



Figure 7. Aluminum Epoxy Sample in Water after 25 Days

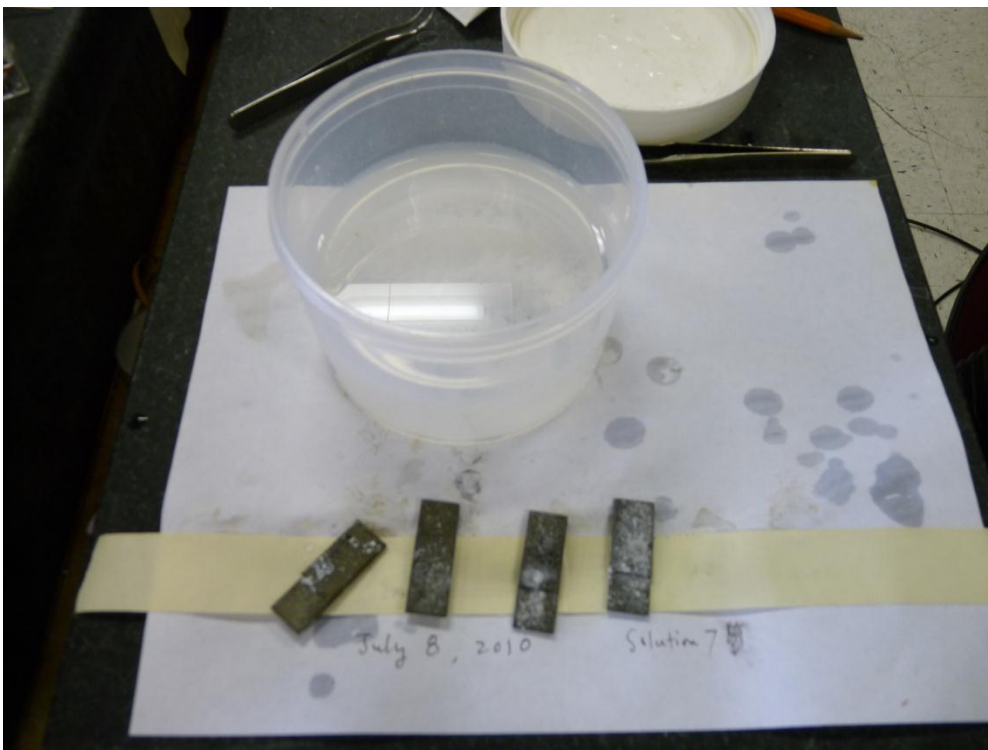


Figure 8. Aluminum Epoxy Sample in Water after 1042 Days

(VII) Results on Functionality Check of Epoxy Joints.

Three kinds of solution were used. The first one was the formic acid (Solution 4), the second one was ISL coolant (Solution 5) and the last one was distilled water (Solution 7). The first two solutions were started with a pH about 2 but both gradually increased to 4. Many bubbles, supposedly to be hydrogen, were generated from the samples after 10 days as shown in Figure 9. Droplets of epoxy samples were also seen clearly detached in this figure. Solution 4 turned into turbid after 2 months and with huge amount of white corrosion precipitations. On the other hand, Solution 5 remained reasonably clear through this 3-year testing period. On the other hand, the epoxy samples in distilled water were definitely survived much longer in this mild condition without detachment. The number of days that the samples found detached in these 3 solutions was compared as shown in Table 2.

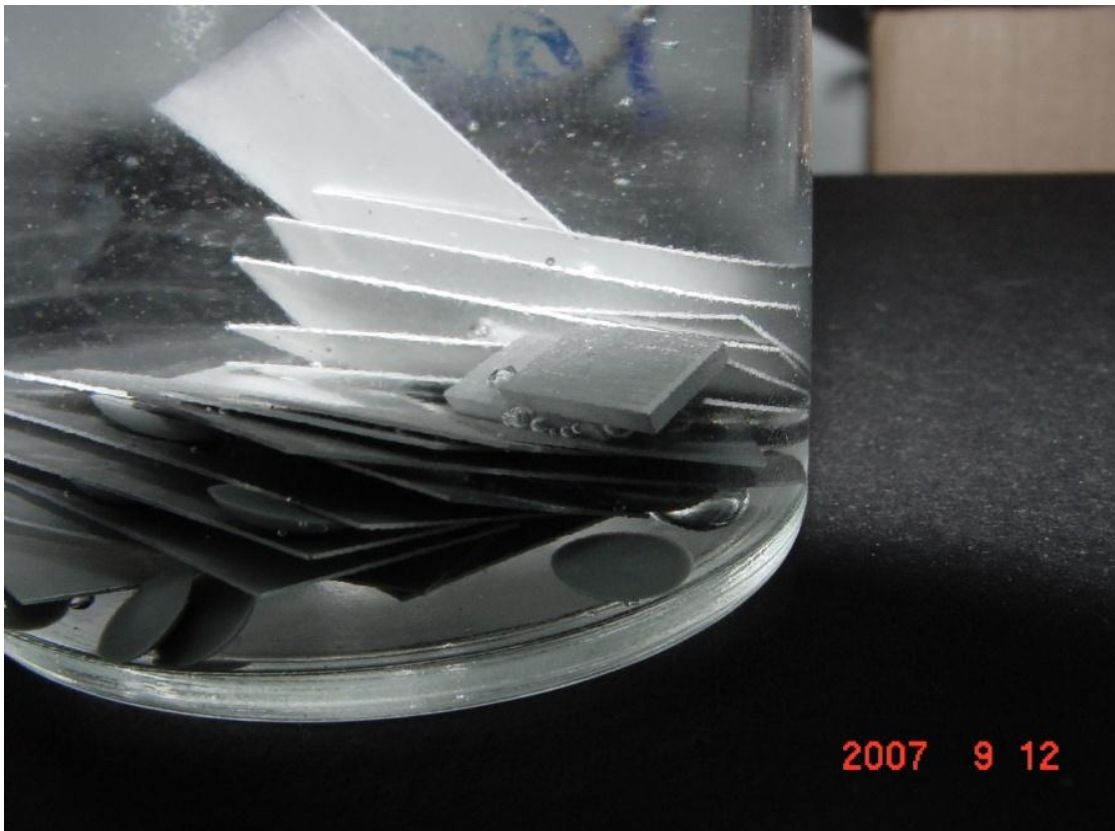


Figure 9. Aluminum Epoxy Sample in Solution 4 after 10 Days

| Sample\Epoxy | Coolant (Solution 4) | | Formic Acid (Solution 5) | | Water (Solution 7) | |
|--------------|----------------------|--------|--------------------------|--------|--------------------|--------|
| | 2216 | DP 190 | 2216 | DP 190 | 2216 | DP 190 |
| Droplet | 10 | 10 | 2 | 2 | 750 | 750 |
| Dog-Bone | 11 | 7 | 2 | 2 | 750 | 750 |
| Lapped | 42 | never | 7 | 77 | never | never* |
| Tubing | never | never | never | never | n/a | n/a |
| Blind Tubing | never | never | never | never | n/a | n/a |

Note: * joints appeared ok without detachment. They were detached after a gentle force was applied at one end.

Table 2. Detachment Comparison of Epoxy Samples in Days

Referring to this table, it appeared that the larger the epoxy surface exposed to the solution, the quicker it would detach from the aluminum base part. So droplet samples detached very quickly from aluminum base and it happened first. This detachment included those dog-bone samples although they appeared not so because of the dog-bone inter-locking structure. Lapped joint samples with 4 thin epoxy side surfaces exposed to solution detached next. Tubing glued joints with minimal exposed epoxy surface never got detached even a force was applied. Also, it seemed that epoxy DP 190 appeared more corrosive resistance than epoxy 2216 when samples were immersed in the acidic solutions.

(VIII) Discussion:

Aluminum is a silvery white and ductile member of the boron group of chemical elements. It is not soluble in water under normal circumstances. Aluminum is remarkable for the metal's low density and for its ability to resist corrosion due to the phenomenon of passivation. That is, a thin amorphous oxide film, which protects the metal from further corrosion is formed as aluminum reacts rapidly with oxygen in the aqueous media. This is an alumina film, and is about 1-10 nm thick. When the aqueous media has a pH value within the stable range between 4 to 9, general corrosion is basically resisted to occur because of this alumina film and aluminum is subject only to staining of the surface and to localized pitting corrosion. However, when this alumina film is in contact with the highly acidic or alkaline corrosive solutions, the alumina film dissolves rapidly and the general corrosion occurs over the entire aluminum surface.

Aluminum is the most widely used non-ferrous metal, and since its alloys provide a wide range of excellent engineering properties, aluminum alloys are very popular in the industry. Taking the ISL cooling system as an example, aluminum alloys 1100, 5051 and 6061 were used. In addition, aluminum fillers wires 4043 and 5356 might have been used also for welding the aluminum parts. Aluminum alloys are made when some other elements are added during the manufacturing phase. The most commonly added elements to the aluminum solution are copper, magnesium, silicon, manganese and zinc. With these elements added within the aluminum solid solubility limits, the corrosion potential of aluminum can be modified. Generally, there are seven kinds of aluminum alloy available in the market and their basic features are described in Table 3.

| | |
|------|--|
| 1xxx | Unalloyed (pure) >99% aluminum. They are characterized by excellent corrosion resistance, high thermal and electrical conductivities, low mechanical properties, and excellent workability. Iron and silicon are the major impurities. Under many conditions, corrosion resistance decreases slightly with increasing alloy content. |
| 2xxx | Copper is the principal alloying element, though other elements like magnesium may be specified. Less resistant to corrosion than alloys of other series, which contain much lower amounts of copper. |
| 3xxx | Manganese is the principal alloying element. Have very high resistance to corrosion. |
| 4xxx | Silicon is the principal alloying element. Silicon can be added in sufficient quantities (up to 12%) to cause substantial lowering of the aluminum melting range. For this reason, aluminum-silicon alloys are used in welding wire and as brazing alloys for joining aluminum, where a lower melting range than that of the base metal is required. The alloys containing appreciable amounts of silicon become dark gray to charcoal when anodic oxide finishes are applied. |
| 5xxx | Magnesium is the principal alloying element. These alloys possess relatively good welding characteristics and relatively good resistance to corrosion in marine atmospheres. When magnesium is used as a major alloying element or with manganese, the result is a moderate-to-high-strength work-hardenable alloy. Magnesium is |

| | |
|------|---|
| | considerably more effective than manganese as a hardener, about 0.8% Mg being equal to 1.25% Mn, and it can be added in considerably higher quantities. However, limitations should be placed on the amount of cold work and the operating temperatures permissible for the higher-magnesium alloys to avoid susceptibility to stress-corrosion cracking. Alloys in which the magnesium is present in amounts that remain in solid solution or is partially precipitated and dispersed uniformly throughout the matrix are generally as resistant to corrosion as commercially pure aluminum. |
| 6xxx | Magnesium and Silicon are the principal alloying elements and they form magnesium silicide (Mg_2Si), which is the basis for precipitation hardening and heat treatment. The Mg_2Si phase is unique in that it is an ionic compound and is not only anodic to aluminum but also reactive in acidic solutions. The resistance to general corrosion is thus slightly inferior than 1xxx and 5xxx but the overall corrosion resistance of these alloys is still regarded as reasonably good. This series of base alloys is most easily welded with the aluminum-silicon type filler alloys, such as 4043. However, the aluminum-magnesium type filler alloys can also be employed satisfactorily with the low-copper bearing 6xxx alloys when higher shear strength and weld metal ductility are required. Age-hardenable alloy 6000 series only slightly prone to inter-crystalline corrosion. Corrosion resistance can be enhanced by heat treatment. The quenching rate must be as high as possible and ageing conditions should tend towards over ageing. |
| 7xxx | Zinc is the principal alloying element, but other elements such as copper, magnesium, chromium, and zirconium may be specified. |

Table 3. Aluminum Alloys and its Alloying Elements

Generally, the higher the magnesium content the better the corrosion resistance. The solubility of magnesium in aluminum solution is very high at elevated temperatures, but small at room temperature. In practice, the magnesium content is limited to 6%.

The manifolds of ISL port-card cooling line were made of 6061 welded with tubing 5052. The filler wire was claimed to be 4043 although the chance of using 5356 could not be wiped out. With reference to the welding table as shown in Table 3 (Ref. 1, p.164), this appeared that 4043 has the best rating

A while 5356 has a rating C (where A is best and D is worst) in the characteristic comparison in corrosion resistance.

| Base alloy to be joined | | | Filler alloy characteristic | | | | | |
|-------------------------|---------|--------|-----------------------------|---|---|---|-----|-----|
| Alloy 1 | Alloy 2 | Filler | W | S | D | C | T | M |
| 6061 | 5052 | 4043 | A | D | C | A | A | ... |
| 6061 | 5052 | 5356 | B | B | A | C | ... | A |

Notations: W: ease of welding (relative freedom from weld cracking);
S: strength of welded joint in as-welded condition; (fillet welds specifically)
D: ductility (rating based on free bend elongation of the weld);
C: corrosion resistance in continuous or alternate immersion of fresh/salt water;
T: performance in service at sustained temperature >65°C;
M: color match after anodizing

Table 4. Characteristic of Aluminum Filler Alloys

Aluminum is prone to pitting corrosion in aqueous media close to neutrality within a pH range of 4 to 9. Under these conditions, pitting corrosion depends more on the quantity of anions than on variation in the pH value of the aqueous media. Scratched, scraped or ground surfaces are micro-flaw sites at which corrosion preferentially develops as the natural oxide film at these sites is less resistant. These sites are anodic with respect to their vicinity.

Acetic acid CH_3COOH and formic acid HCOOH were the main weak acids found in the ISL coolant and they are belonged to acyclic hydrocarbon acid. Acetic acid does not attack aluminum much at room temperature, the higher the acid concentration, the better the resistance actually it will be. However, formic acid has a moderate action on attacking aluminum and can develop pitting corrosion. Aluminum has a fair resistance to formic acid at any concentration at room temperature as long as there is no contamination of the acid. If contaminated with salts, corrosion is severe, and the higher the temperature, the higher the dissolution rate will be.

Many alloys rely on a fairly thin metal oxide surface layer, or "passive film", to impart corrosion resistance to the bulk material. As alloys are not homogeneous, the surface region is not homogeneous either. Commercial alloys contain numerous inclusions, second phases, and regions of composition-based heterogeneities. These regions are believed to provide

initiation points for pitting in alloys. In addition, pitting can occur in homogeneous alloys depending on the presence of certain species like chloride ions in the environment.

With reference to ref. 5, a generalized picture of the propagation of a pit in aluminum in aerated solutions containing chloride ions is shown in Figure 10. The pH of the environment is assumed to be in the range of about 5 to 9.

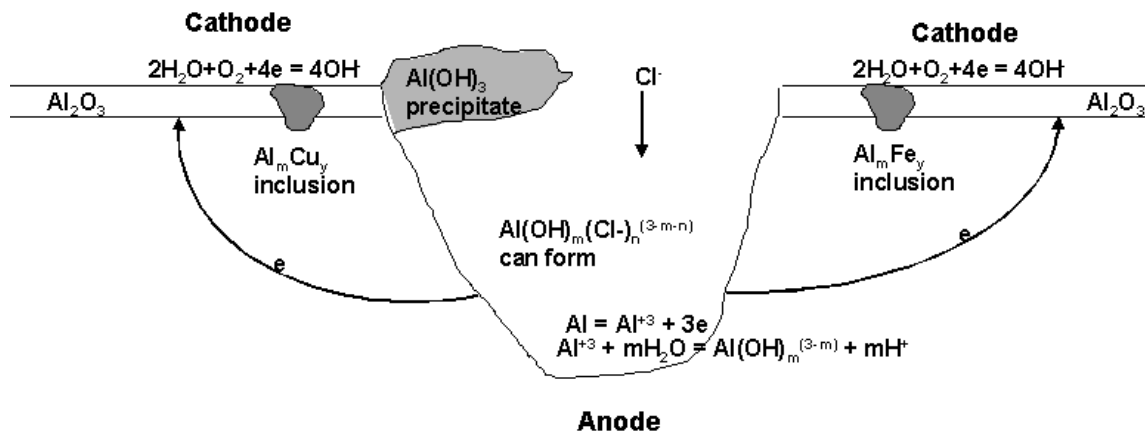


Figure 10. General Pitting Corrosion when Chloride Ions are presented

Though the exact mechanism of aluminum pit initiation depends on the actual alloy type, some general characteristics of the process can be summarized as follows.

- Microflaws exist in the aluminum oxide layers that provide passivity to the alloy. The surface is very likely a hydroxide form of aluminum.
- **The chloride adsorption in the microflaws, if any, might aid in pit initiation.**
- Alloys of aluminum contain intermetallic compounds can form dissimilar metal junctions at the surface. For example, 2000 series aluminum contain copper aluminide inclusions and 3000 series aluminum contain iron-aluminide inclusions. The copper aluminide inclusion may decompose to redeposit copper on the surface.
- A potential difference is created between the "unflawed" aluminum surface and that created by pre-existing flaws, chloride adsorption in flaws, or the intermetallic inclusions.

- As a result of the potential difference, oxygen reduction on the "unflawed" surface or on the intermetallic compound drives the anodic dissolution in the region of the flaw or on the aluminum surface adjacent to the intermetallic compound.

The result is a micropit. Some of the micropits repassivate. Some propagate to larger pits. The above figure shows the process as the pit is propagating. The propagation process has the following characteristics.

- Aluminum dissolution proceeds within the pit especially at the bottom or base of the pit.
- Aluminum ions react with water (hydrolysis) to form aluminum hydroxide cations and hydrogen ions.
- The formation of hydrogen ions decreases the pH relative to the environment outside of the pit further accelerating the dissolution process.
- **In a chloride environment, chloride ions increase in concentration to maintain charge neutrality. These ions can react with the aluminum hydroxide ions to form chloride containing adducts.**
- Aluminum hydroxide can precipitate at the pit-environment boundary. Sometimes this hydroxide can cover the pit surface but maintain electrolyte contact between the pit and environment.
- Hydrogen ions can be reduced to form hydrogen gas bubbles.
- Oxygen reduction continues on the surface as the cathodic driver. In addition, copper from the copper-aluminide intermetallics at the surface can be reduced further driving the process.

In general, aluminum reacts with 3 water molecules to produce alumina $\text{Al}(\text{OH})_3$ and water. Alumina is insoluble in water and precipitates as a white gel and found in corrosion pits. Some of the pits repassivate, pit penetration is then stopped but it can be restarted. Some propagate to larger pits with penetration so great that the wall of the aluminum body can be completely perforated.

General corrosion resistance of aluminum is not directly related to the amount of oxygen dissolved in water, and that resistance does not differ significantly in aerated and deaerated water. The presence of oxygen, however, leads at most to a more localized corrosion, but has no influence

on pitting depth. It thus stagnant water tank has a higher chance of getting pitting corrosion mainly due to missing of aeration, and thus missing the regular uptake of oxygen. This oxygen uptake contributes to repairing the oxide layer. Water movement regularly eliminates corrosion products and uniformises the cathodic and anodic zones by removing a possible local excess of H^+ and $HCOO^-$ ions. That was possibly what happened in our tests and explains why the pitting corrosion was discontinued after the samples were rinsed with water.

It thus, pitting corrosion was happened in stagnant Solution 1, Solution 3 and Solution 7 in which the pH was between 4 to 9. Aluminum 5052 on its own proved to be the most corrosion resistant and never got any pitting corrosion. Others pitted for a period but stopped. Aluminum filler wires 4043 and 5356 on their own were not that corrosive resistant. They performed reasonably well in the welded assemblies though as the pitting locations were found in the base parts but not on the weld bead.

Here is the summary about the pitted corrosion parts:

- 1100 pitted once but stopped
- 5052 never
- 6061 pitted
- 4043 pitted and became 2 parts
- 5356 pitted
- 4043 welded assembly pitted once on base parts but stopped
- 5356 welded assembly pitted once on base parts but stopped

As of adhesion with the aluminum parts, the surfaces of aluminum alloys are not really conducive to adhesion. The aluminum oxide on top, with varying thickness and composition, lack the microstructure, porosity, mechanical strength, and hydration resistance to form durable bonds with the adhesive. It is thus desirable to remove this aluminum oxide and develop a direct bonding between the aluminum surface and the adhesive. However, unless special pretreatment like acid etching is done, the bonding between the oxide layer on the aluminum surface and an adhesive is what being dealt with in general situations. Surface roughness increases the area of contact between the aluminum substrate and the adhesive, and thus will develop an effective mechanical interlocking. So if the surface oxide layer is made sufficiently rough, the adhesive can be allowed to key into the aluminum surface

directly. The greater the interlocking achieved, the stronger the bond it will be because more energy is needed for a crack to propagate at the interface.

Aluminum oxide surfaces have high surface energies and are more wettable than low surface energy surfaces like Teflon. Yet aluminum surfaces that have been degreased only prior to bonding can have voids at the adhesive/oxide interface. Voids at the interface will act as stress concentrators, reducing the mechanical strength at the interface. In addition, such unfilled pores at the interface will allow aqueous media to more readily penetrate the interface, and this is generally one of the major causes of bond failure.

Taking the mild water as an example as the aqueous media in contact with the adhered joint of aluminum, it is well known that water attacks these adhesive/aluminum bonds notoriously. This is because the joint substrates, such as metal or metal oxides, have very high surface energies and water will permeate through the organic adhesives which are with a lower surface energy. Analyses of the two sides of the failed bond show that the failure is often initially cohesive – that is, it takes place within the adhesive, then the locus of failure moves to the adhesive-oxide interface.

Water damages the interface in two ways: it disrupts the oxide/adhesive chemical interactions and it changes the microstructure and chemistry of the oxide layer itself. Hydration of the aluminum oxide layer occurs and this converts aluminum oxide to the weak gelatinous aluminum hydroxide. Failure surface analysis reveals that the hydroxide layer is normally attached to the adhesive side, suggesting that adhesion of the hydroxide to aluminum is very weak. Thus, once a hydroxide layer is formed, it will be separated easily from the base aluminum, causing failure of the joint.

Since the solutions used in this test were acidic and more corrosive than water, it was therefore the epoxy droplets, which had a large epoxy surface exposed to the coolant or formic acid, detached from the aluminum base in a short period of several days. Similar joint detachment was happened on those dog-bone samples although they appeared not so because the droplets on both aluminum surfaces were structurally inter-locked. Lapped joint samples were also found detached because it had 4 smaller sides of epoxy surfaces exposed to the acidic solution. The ingress of acid was still high enough to make them detach ednext. As the cylindrical joint samples had

only 2 sides or 1 side of tiny surfaces exposed, it lasted longest and were not detached even at the end of writing this report.

(IX) Conclusion:

General corrosion over the entire surface was observed for those aluminum samples immersed in solution with pH under 4. Pitting corrosions were found in those aluminum samples immersed in solutions with pH range from 4 to 9. Epoxy joint in aluminum cylindrical tubing samples appeared no detachment even after 960 days of immersion while other types of epoxy joint samples detached in early days.

(X) Acknowledgement:

I would like to express my deep gratitude to Anna Pla-dalmau who has helped me to prepare the cooling solutions for the testing and made comments on this report.

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